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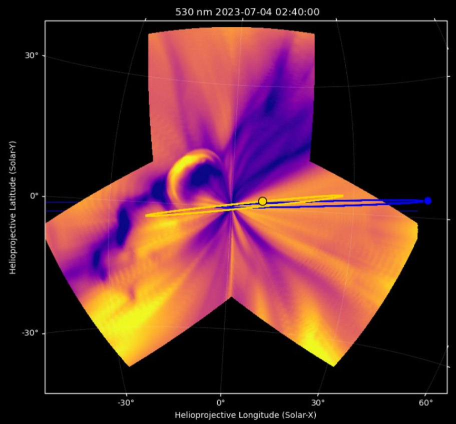
CENTER FOR ASTROPHYSICS
HARVARD & SMITHSONIAN

Diving through the plane of sky : Using PUNCH to inform in situ to solar magnetic connections



Samuel T. Badman

PUNCH 5 - June 20, 2024

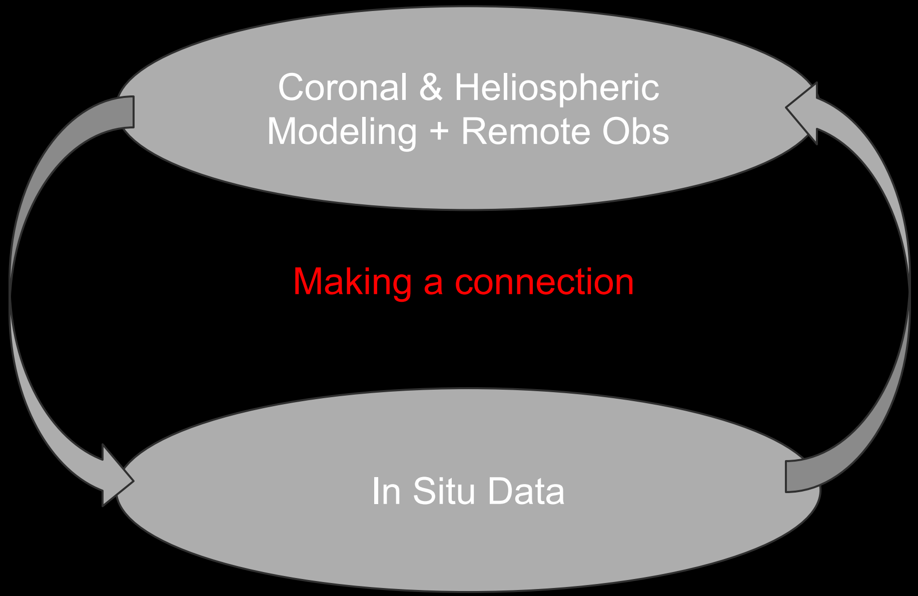
Connecting In Situ Data and Coronal Models : Motivation

- Establishing a connection between a given interval of in situ data and a source on the Sun

- Two-way feedback :

    - What conditions on the Sun caused the in situ data signature? What heliospheric structure did disturbances propagate along? What targets can remote observers zoom in on?

    - How good is our model representation of the heliosphere? Is the predicted connection consistent with the key features of the data?



Parker Solar Probe and Solar Orbiter : In Situ Instrumentation

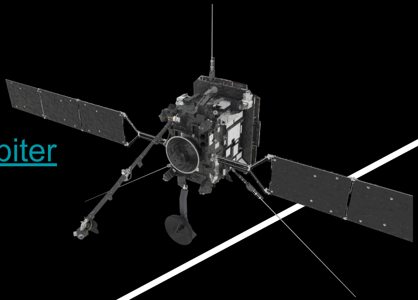
- **E** & **B** fields (RPW/MAG)
- Thermal plasma distributions and moments (SWA)
- Energetic Ion distributions and composition (EPD)
- Heavy ion composition (HIS)

0.046 au (2025)
(9.8 Rs)

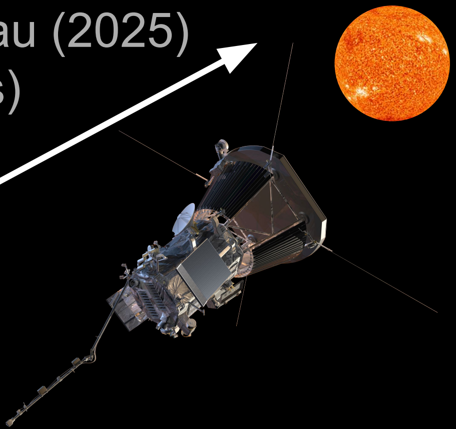
0.3 au

0.7 au
(~Venus)

1au



Solar Orbiter



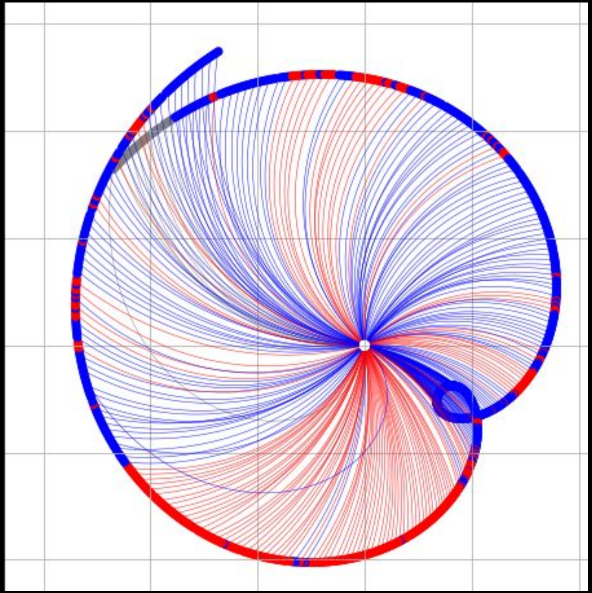
Parker Solar Probe

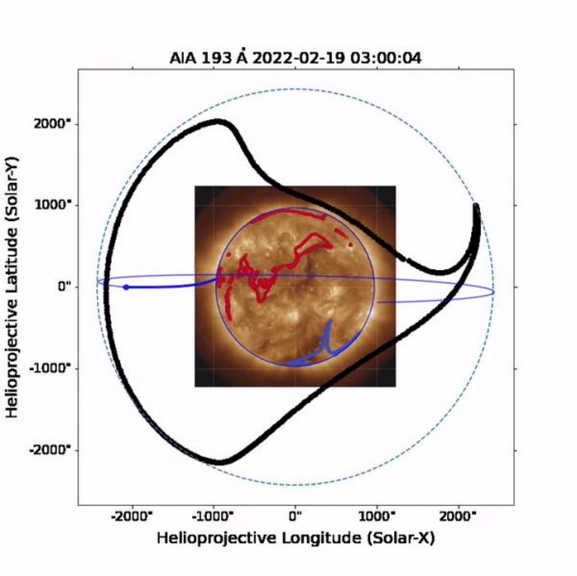
- **E** & **B** fields (FIELDS)
- Quasi-thermal noise electron density (FIELDS)
- Thermal plasma distributions and moments (SWEAP)
- Energetic Ion distributions and composition (IS⊙IS)

Modeling Magnetic Connectivity

Heliosphere >

- Ballistic Approximation (e.g. Dakeyo+2024)
- WSA empirical stream interactions
- Hydrodynamic modeling (e.g. ENLIL, HUX, HUXt)
- Magnetohydrodynamic modeling (e.g. HELIO-MAS, MS-FLUKSS, AWSOM, EUFORIA)





< Corona

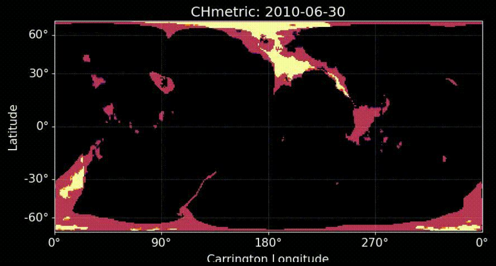
- Field line tracing in 3D numerical grid (PFSS, PFSS/SCS, Coronal MHD)

Output: Estimated mapping
(Spacecraft: x,y,z,t) -> (Source: t_emit, lon, lat)

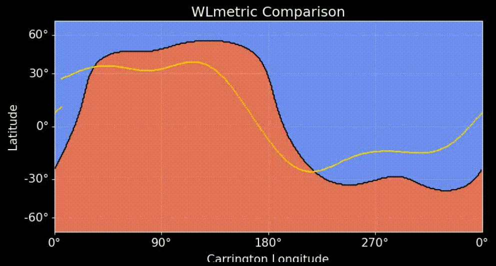
Testing Magnetic Connectivity

Remote constraints e.g.

Kisare+ CfA REU/AGU 2023



Matching between coronal holes and dark regions in EUV

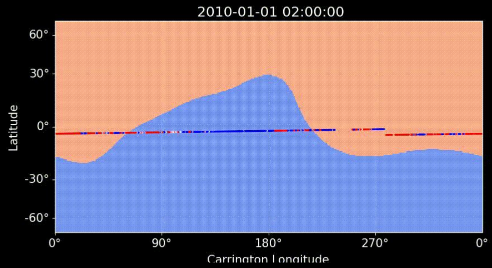


Matching white light streamer location to predicted heliospheric current sheet

In Situ Constraints e.g.

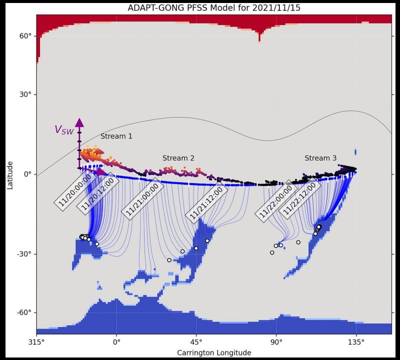
Kisare+ CfA REU/AGU 2023

Matching in situ polarity measurements to modeled HCS



Badman+2023 JGR

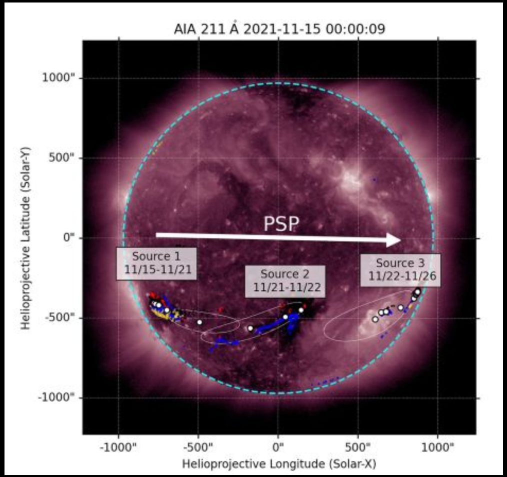
Matching velocity stream structure to mapped coronal hole geometry



Frozen-in compositional characteristics
(See Y. Rivera talk this afternoon)

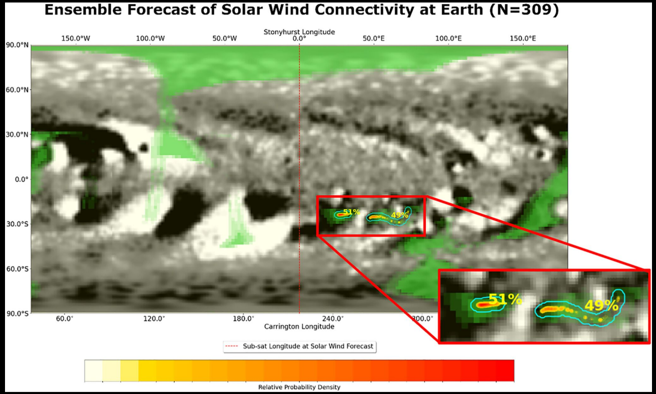
Assessing Source Mapping Sensitivity

- In addition to trying to validate the modelled connection with physical observables, we can quantify how *sensitive* the connection is to assumptions



Inter-model consensus
(Badman+2023 JGR)

Do different models predict the same connection?



Ensemble boundary conditions and mapping parameters (Da Silva+2023 JGR Space Weather)
(See also Koukras+2022 and http://connect-tool.irap.omp.eu/)

Does the inferred source change if different parameters and boundary conditions are used? (e.g. perturbing boundary conditions, transit time, starting spiral longitude)

Assumptions and Uncertainty (that PUNCH might help with!)

- We currently can answer if (1) our connection is **consistent** with models and observations, and (2) if small perturbations to the connection method changes the answer a lot, but many issues still remain e.g.:

Steady/mean/radial flow assumption

- No accounting for small scale structures on connection e.g. field line meandering
- Ignores meridional flows (constant latitude)

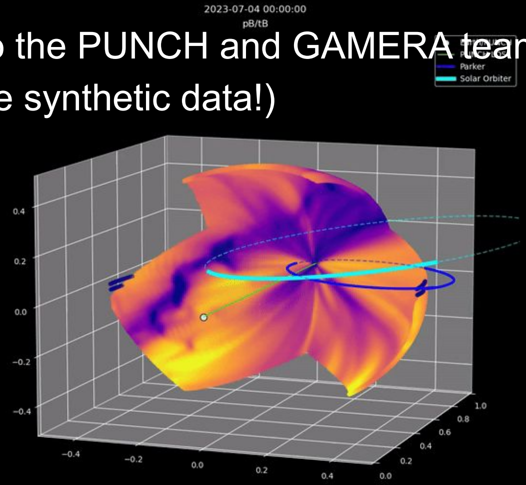
Generally time-independent modeling

- Interplay of transients and background flow unaccounted for
- Magnetic connectivity assumed steady, and (for CH connections) reflected in EUV emission

Transit time uncertainty

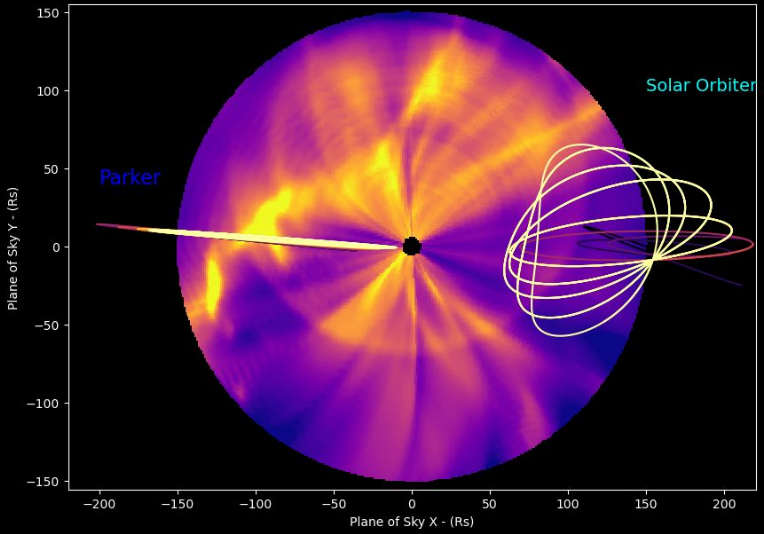
- Depends on acceleration profile of plasma parcel
- Depends on disturbance or flow type to be mapped

Bringing PUNCH into the Picture (thanks to the PUNCH and GAMERA teams for the synthetic data!)



- Parker and Solar Orbiter spend much of their orbits in the FOV of PUNCH

- Parker will routinely sample inside the NFI field of view out to outer edge. Solar Orbiter will traverse a substantial wedge in latitude.

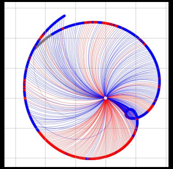


- Both spacecraft will cross the Thomson sphere of PUNCH twice per orbit for portions of the year.

- For part of the year, Parker’s orbit could be tangent to a large portion of the PUNCH Thomson sphere

- For far-side perihelia, Parker’s inbound and outbound passes will sample radial evolution over both solar limbs

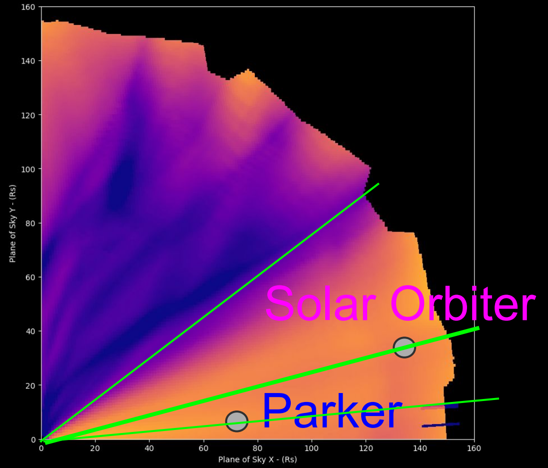
PUNCH and Magnetic Connection Synergies



Steady/Mean/Radial Flow

PUNCH can

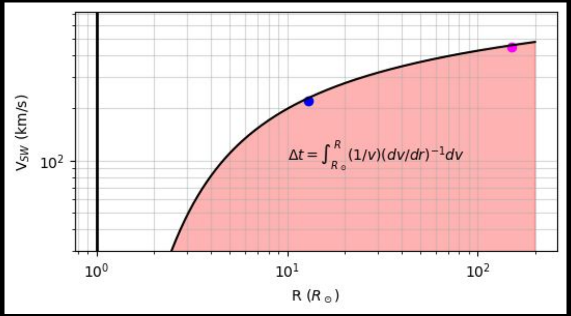
- Critically assess small scale variation at locations of Parker and Solar Orbiter
- Observe meridional flows on different time and length scales and weigh in on a latitudinally independent Parker spiral



Transit-time Uncertainty

PUNCH can

- Provide solar wind acceleration profiles tied to in situ measurements and improve estimates of plasma parcel transit timing.

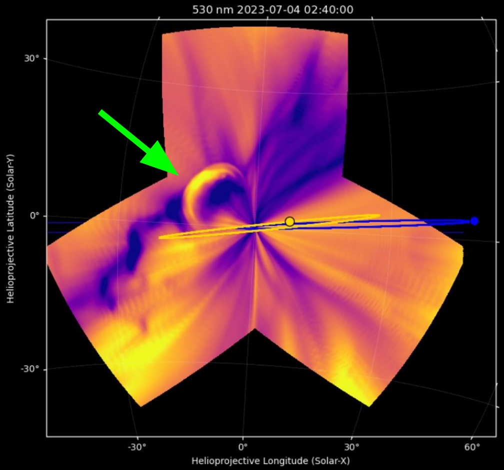


https://github.com/STBadman/ParkerSolarWind

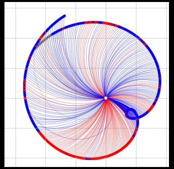
Time-Independent Modeling

PUNCH can

- Provide synoptic observations of transients and fluctuations and assess the extent to which they interrupt the steady/average flow picture

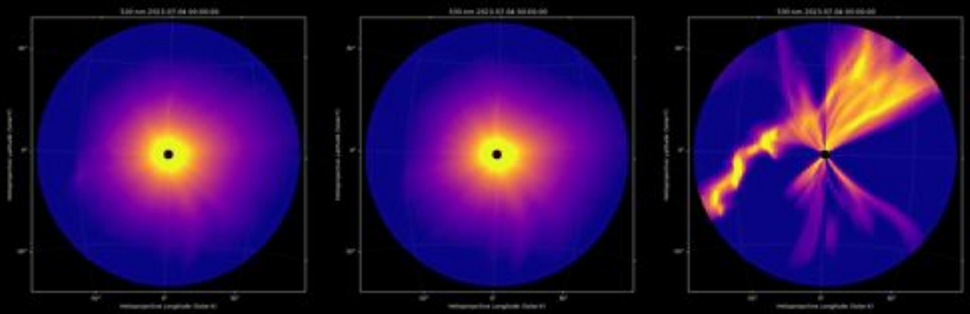


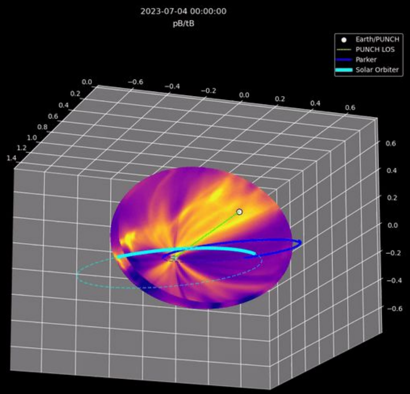
PUNCH and Magnetic Connection Synergies



Magnetic Connectivity can (e.g.) :

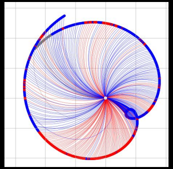
- Provide multipoint (including at different radial distances) in situ constraints to directly compare with PUNCH observables and 3D imaging (e.g. density, velocity, alfven mach number) :





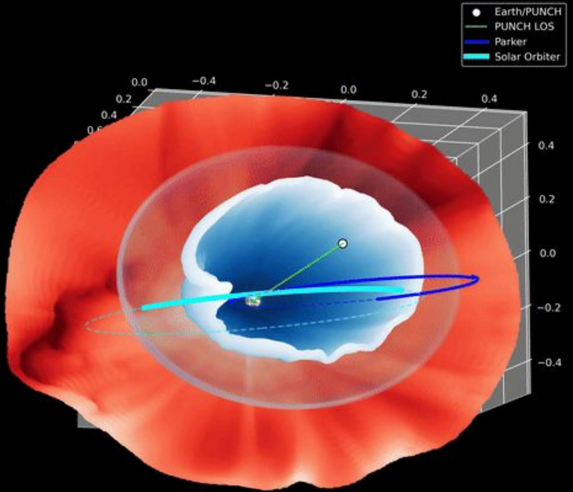
- Insert microphysical insight into PUNCH observations e.g. relating coronal jetting and/or heliospheric switchbacks to the larger scale flows PUNCH can see.

PUNCH and Magnetic Connection Synergies



Magnetic Connectivity can (e.g.) :

- Provide multipoint (including at different radial distances) in situ constraints to directly compare with PUNCH observables and 3D imaging (e.g. density, velocity, alfven mach number) :
    - **Discriminating +/- solutions of scattering sources from the Thomson Sphere**
      https://middlecorona.com/notthemiddlecorona/VAPOR_output/West%20Solar%20Day%202023.pdf



< Thanks to Matt West for this data!

- Insert microphysical insight into PUNCH observations e.g. relating coronal jetting and/or heliospheric switchbacks to the larger scale flows PUNCH can see.

Conclusions and Outlook

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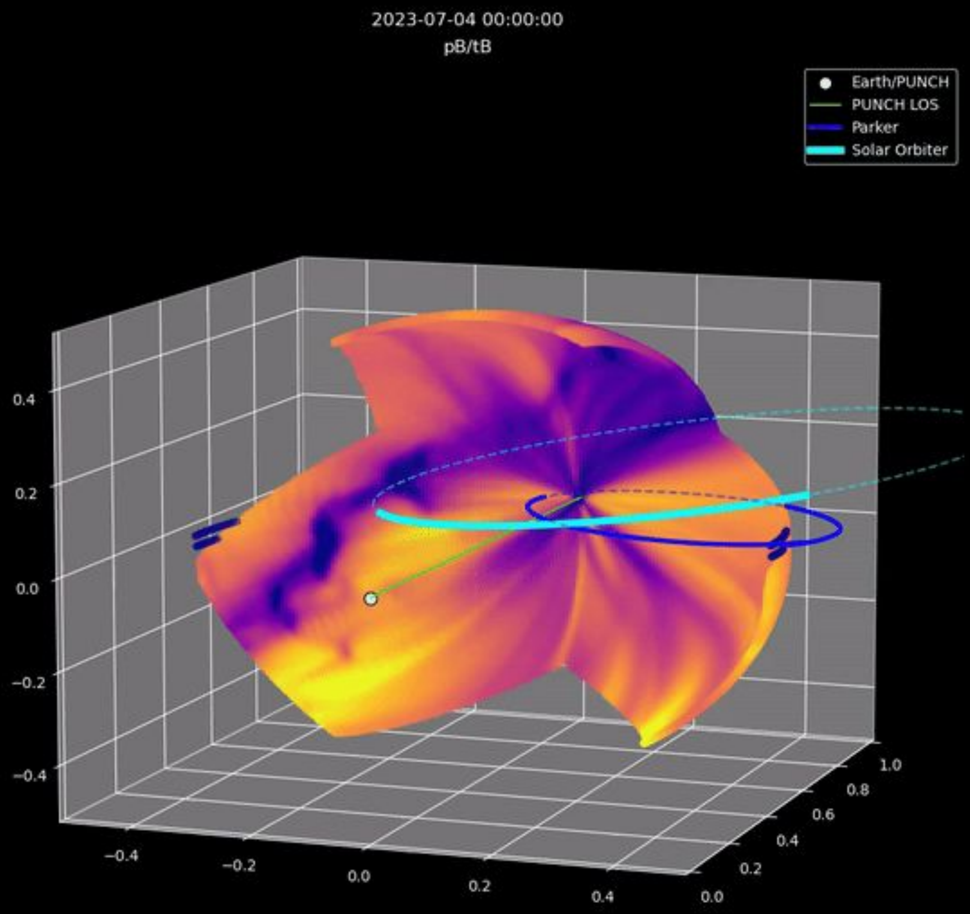
- Connecting in situ data to models has never been more promising than right now with Parker (10-155 Rs,+/- 7 deg), Solar Orbiter (60-215 Rs, up to +/-30 deg)

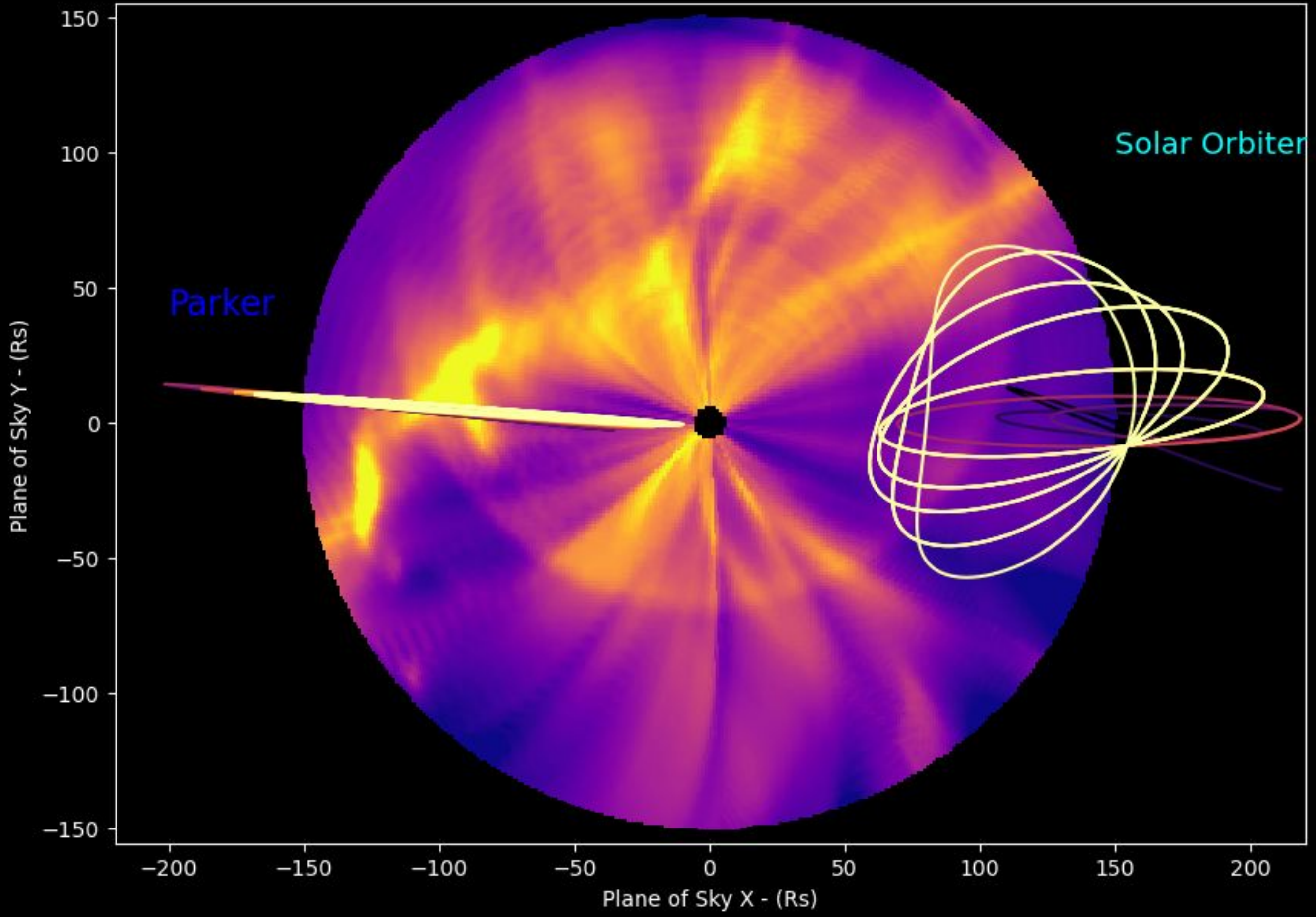
- PUNCH offers remote obs of steady and transient flows at all latitudes in the (~)plane of sky 1.5-180Rs

- PUNCH will allow an approximate assessment of continuous solar wind conditions in almost the entire interior space being reconstructed from making solar wind connections, potentially allowing improvements and critical assessments of uncertainties and assumptions in modeling connections.

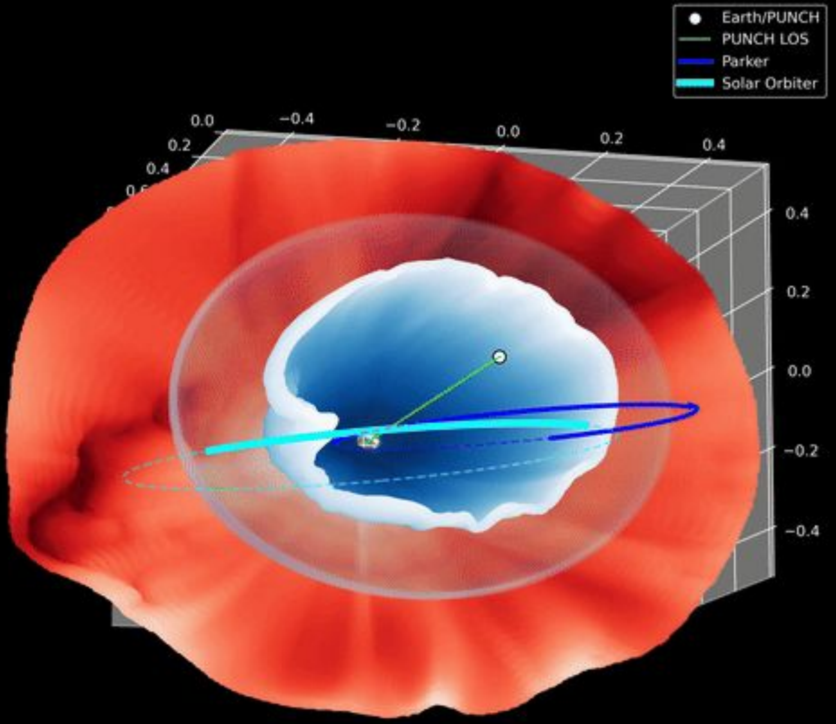
Backup : Full size Synthetic Data Movie



Backup: Full size FOV Image



Isometric Visualization of Sign Ambiguity



Abstract

The heliosphere has never been better instrumented with in situ and remote observatories both on and off the Sun-Earth line. A key goal of almost all such missions is to combine these two complementary methods of measuring the Sun's atmosphere both low down and out in the solar wind with a view towards a system level understanding. PUNCH will be launching into this landscape and provide a unique perspective with continuous observations of steady and transient flows spanning an unprecedented range of distances and scales. In this talk, we will discuss the synergy between the goal of connecting in situ data back to the Sun and the PUNCH mission. Specifically, we will discuss how the continuous field of view of PUNCH can provide constraints to such linkage in a way previously only achievable with numerical models, and conversely, how identification of in situ data with individual solar sources can be used to validate PUNCH observations and potentially break the degeneracy in interpretation of the 3D location of solar wind structures.